MULTIDISCIPLINARY DESIGN AND FLIGHT TESTING OF A REMOTE GAS/PARTICLE AIRBORNE SENSOR SYSTEM

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Abstract

The main objective of this paper is to describe the development of a remote sensing airborne air sampling system for Unmanned Aerial Systems (UAS) and provide the capability for the detection of particle and gas concentrations in real time over remote locations. The design of the air sampling methodology started by defining system architecture, and then by selecting and integrating each subsystem. A multifunctional air sampling instrument, with capability for simultaneous measurement of particle and gas concentrations was modified and integrated with ARCAA's Flamingo UAS platform and communications protocols. As result of the integration process, a system capable of both real time geo-location monitoring and indexed-link sampling was obtained. Wind tunnel tests were conducted in order to evaluate the performance of the air sampling instrument in controlled non-stationary conditions at the typical operational velocities of the UAS platform. Once the remote fully operative air sampling system was obtained, the problem of mission design was analyzed through the simulation of different scenarios. Furthermore, flight tests of the complete air sampling system were then conducted to check the dynamic characteristics of the UAS with the air sampling system and to prove its capability to perform an air sampling mission following a specific flight path.

1 Introduction

THE state of the air is an important factor for the environment and life quality. It affects the health of the community and directly influences the sustainability of our lifestyles and production methods. Therefore, the importance of monitoring and assessing indoor or outdoor air quality is essential and globally considered. There are a number of devices to sample air particles and gases, and most of them are stationary at the sampling location [1, 2]. Being stationary devices, their coverage is limited. Consequently covering extended zones requires a vast amount of instruments, which results in a high cost solution. In addition, it is important to enhance the capability to sample air in regions in which the terrain is inaccessible or where there is a chemical threat[3]. On the other hand, with a portable flying air sampling system, a larger coverage would be possible and the system could be designed to perform different tasks and missions such as monitoring particle concentration and toxic gases.

Different remote sensing techniques have been using for environmental surveillance. In this sense LiDAR have been applied for carbon accounting and forest management [4, 5] and satellites analysis to measure the air quality [6, 7]. Furthermore, mechatronic devices have been used for soil monitoring [8]. The main limitations of such systems are related to resolution and system cost [9]. Other approaches have been focused in the use of UAS for remote sensing and data collection. This field has been explored by a number of researchers, most of them have published information related to vegetation management, control and power line inspection [10-15]. Conversely, UAS have also been used air sampling and environmental analysis. [16] integrated a biosensor system on a small and remotely piloted airplane in order to collect aerosolized bacteria in flight, identify them and

transmit the data on the ground. Nevertheless this system required human intervention for control and planning proposes.
This system is mainly limited by relative long sampling intervals, the coordination of two aerial vehicles and ground-based detection of spores. UAS for gas analysis have been used to detect plumes in the proximities of craters flying at high altitudes to measure the total black carbon concentration of particles over the Indian Ocean ([18], [19]) . Such systems were equipped with meteorological packages for measuring pressure, temperature, and relative humidity, particle counters, and aerosol absorption photometers. Nevertheless, no details on precise control, wind tunnel, mission planning of the UAS were described in these solutions. Patria mini-UAS is another example of a UAS developed for air sampling [20, 21]. In their research the authors developed the UAS to sample air and to detect gamma-ray in real time. The air sampler and the filter which captures the particles were developed using CFD (computational fluid dynamics) software and wind tunnel testing. Even though this system was tested in real atmospheric conditions, information on flight tests results was limited. Our air sampling strategy consists of the use of an UAS integrated with an air sampling device in order to measure gas concentrations in remote locations and transmit this analyzed information in real time to the ground station. This research embraces the design of the air sampling methodology defining system architecture, wind tunnel testing, simulation of different scenarios and flight tests of the complete air sampling system. We believe that the research presented here is the first one that covers an entire framework that includes wind tunnel testing, simulations and experimental results for UAS.
Dingus et al. (Dingus, 2008; Schmale, et al., 2008;) have undertaken air sampling experiments using a UAS (Senior Telemaster model aircraft) where autonomous flight commands were provided by an autopilot system onboard. A total of four petri dishes were used on each UAV, two on each wing to undertake samples during flight. The petri plates were placed in each commanded by the UAS controller to open, take a sample then close to avoid contamination. This type of air sampling solution is limited to four samples during a single mission. Thus it cannot illustrate a multiple sampling as a function of time in different geographic areas. In other research, Anderson et al. (Anderson, et al., 1999) used a multi-channel fluorimeter and a custom ram-air-driven cyclone particle collector for air sampling experiments. Purified polycyclonal rabbit antibodies were fluoresced using fluorescent dye and dispersed in a predefined test area. The onboard fluorimeter (controlled by the ground station), provides real time detection of fluorescent particles in the atmosphere. This fluorescent technique has been used by several researchers in the community for particle detection (Ligler et al., 1993, Ligler et al. 1998, Sanders et al., 2001, Zhang et al, 2002). The use of particle counters/sizers onboard UASs provide an excellent method of real time identification of particles of known sizes in the atmosphere if the particles are present in large concentrations. Corrigan et al. (Corrigan, et al., 2008) performed a similar set of experiments, where total and optical particle counters where employed to detect black carbon concentrations over the Indian Ocean using autonomous UASs. The UASs were flown at a range of altitudes to generate a vertical profile of the atmospheric black carbon concentrations. However, pathogens are typically present in much lower concentrations, and not fluorescent. Thus, the most suitable method of pathogen detection is the collection and post processing of capture spore samples (by a trained plant pathologist).

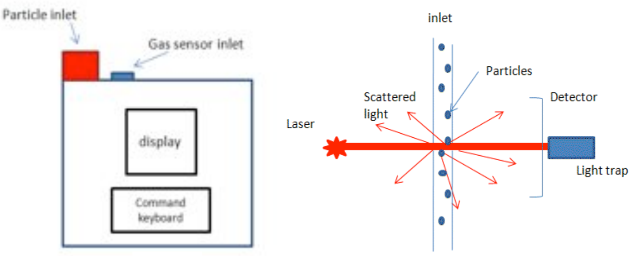
The rest of the paper is as follows: section II describes the system architecture, section III shows the development of an experimental methodology and wind tunnel tests, section IV describes the installation and integration process of the air sampling instrument, section V concerns the simulations performed and the mission design, section VI describes the flight tests conducted.

2 System Architecture

The aim of the system is to fly autonomously in a desired area, whilst it is sampling and transmitting directly to the ground station. This research project was designed using a system engineering research approach[22]. In the architecture the ground control station is continuously in contact with the UAS via a telemetry link, by means of a Microhard Spectra920A radio modem. Such radio modem take standard RS232 serial data and transmits it over a 900MHz spread spectrum link with a configured baud rate of 57600bps. The MicroPilot autopilot receives data from the ground, through the telemetry, and from the sensors onboard and act on the servos to control the UAS. The servos used to move the control surfaces are eight Hitec HS-645 MG. Whilst the control actuation servos are powered by one 6v 3600mAh NiMH battery. The air sampler is mechanically mounted and secured to the UAS, and integrated with the UAS autopilot.

2.1 UAS Platform

In this research a fully modular and light weight UAS called Flamingo “Carla” UAS was used [23]; The Flamingo airframe is manufactured by Silvertone and the avionics are developed integrally by ARCAA. This UAS is designed to operate in the under 20kg AUW class of UAS; therefore it is possible to avoid issues and costs incurred by larger UAS which are subject to more stringent Australian Civil Aviation regulations.



a) b)

Fig. 1. a)Air Sampling device schematic. b) Light scattering photometer principle of operation

The Flamingo is constructed entirely with modern composite materials. Indeed, the wing and the fuselage are designed to have high efficiency so that minimum power is required for its performance. The main design parameters were related with the aircraft specifications of a wing span of 4 meters and the maximum payload capability of 8 Kg.The main limitation of the Flamingo for an air sampling mission is the payload capability. In fact, the majority of the air sampling devices commercially available are heavy and with odd dimensions, therefore careful considerations were allocated to the selection and modifications of the air sampling device.

2.2 Air Sampling Device

Different devices for air sampling were explored in this research. The basic concept was to create an UAS for air sampling that could either store or send data in real time to the ground station. A light scattering photometer device was chosen for its feature to provide multiple simultaneous measurements of particle concentration and gas concentration (by means of different sensors). The device is portable, battery operated, multifunctional air sampler instrument (Fig. 1).

In this device, air travels through the impactor, where the larger and heavier particulate sticks on a greased plate. Lighter particles pass through an optical laser photometer, and then are trap in a gravimetric cassette. The remaining clean air passes through a pump, then through a pressure sensor, and lastly to the outlet on the back of the instrument. The flow rate, is constant and controlled. A differential pressure sensor on the PC board is used to measure the pressure drop across the orifice above.
The photometer had a resolution of 0.1 µm- 100 µm with a concentration range of 0.001 to 199.9 mg/m3. Its relative small dimensions (19 x 19 7 cm), low weight (1.3 Kg) and long battery duration (8hrs operative) made it adequate for the Flamingo UAS. Furthermore, this sensor was modified to allow real time monitoring (See

Section 4.1).

2.3 UAS Autopilot

One of the systems used that allows a fully autonomous flight on the Flamingo is the autopilot. The UAS uses the MicroPilot 2128heli [22], which can be used for a wide range of UAS: from highly functional high speed UAS through backpack UAS to micro UAS. The capabilities of this autopilot include airspeed hold, altitude hold, turn coordination, GPS navigation as well as autonomous launch and recovery. The software used in the ground control station is HORIZONmp which allows creating and simulating mission, adjusting parameters, monitoring flight [25, 26].

3 Development of an experimental methodology and wind tunnel tests

An experimental methodology was developed for wind tunnel and flight tests on the air sampling system before flight test. The development of an experimental methodology is important in order to perform repeatable measurement and controlled experiments. The wind tunnel was used to simulate the air flow at the inlet of the air sampling device during the flight of the UAS. It was necessary to use and develop an aerosol generation method to simulate spore or particles concentration in a safe manner. Two recommended options to produce particles or simulated spores were studied

3.1 Atomized polystyrene latex

Polystyrene Latex (PSL) is one recommended substance to simulate particles in an aerosol testing [27]. PSL is non toxic and particle size is dependent on requirements. In addition it provides consistency in regards to the repeatability of the test. Particles generated from PSL are typical of an idealized mono-disperse aerosol, composed by solid spheres. An aerosol generation method, based on a common atomizer, was set up in the wind tunnel.

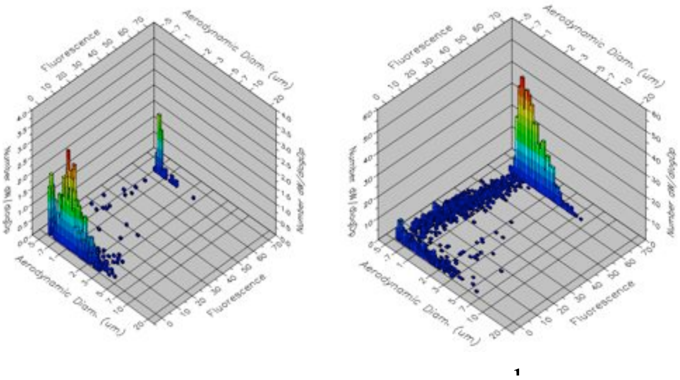


Figure 2. a) Polystyrene polymer concentration in

Figure 2 shows some results of the test aerosol produced with this method. The number dW/dlogDp refers to concentration of particles per cubic centimeter, the aerodynamic diameter is related to particle size, and the fluorescence value marks the particles in order to distinguish the particles produced by the atomizer and the other particles The wind tunnel setup is described as follows:

[1] Compressed air source: the atomizer is connected to a source of compressed air at 3 bars. This allows the water with PSL to be continuously atomized.
[2] Atomizer: The atomizer is a portable device which employs pressurized air (up to 3 bars) to disperse particles suspended in a solution. It is filled with distilled water and PSL. Between 10-20 drops of PSL are usually enough to have a high concentration of particles.
[3] Dryer filter: the water droplets in the aerosol are absorbed by the filter. The result after the filter is a mono-disperse aerosol with 1 μm sphere of PSL.
[4] Particle sizer: is an instrument to monitor the aerosol concentration within the wind tunnel in real time. The PSL particles, produced with the atomizer, are marked with fluorescence, with an excitation value of 488nm (blue). In this way the instrument can analyze the aerosol and distinguish the particles produced by the atomizer and the other particles in the air or inside the wind tunnel (dust, pollution).

[5] Laser generator: is connected to the particle sizer, and provides the laser beam to detect particles.
[6] Laptop and software: is connected with a serial cable to the particle sizer. By means of special software, it is possible to monitor main data about the aerosol generated (such as particle concentration, fluorescence level, aerodynamic diameter of the particles, etc).

The main drawback of this generation method is related to the quantity of particles produced. It was observed that the concentration level of the particles marked with fluorescence (PSL particles) was about 1-2 particles/cm3. Such value was even lower than the concentration level of the air particles within the wind tunnel (2.5 particles/cm3). This means that without the fluorescence it would be impossible to distinguish the test particle produced by the atomizer from the rest of the particles. The dispersion of the PSL within the working section of the wind tunnel was also of concern. It was seen that releasing the particles generated by the atomizer into the flow stream in the same direction of the airflow (see Fig. 2a) provides a more even distribution within the working section of the wind tunnel.

3.2 Smoke Machine and Sugar

The second aerosol generation method explored in this research uses dissolved sugar through a smoke machine. 80grams of sugar were dissolved with 4ml of dye UVITEX CF 200% (food colouring which fluoresces the sugar particles at an excitation value of 350nm) in 1L of distilled water into the base of the smoke machine. The smoke machine was placed at the base of the wind tunnel airflow input duct. Due to the nature of the smoke machine generator, the dissolved sugar particles produced were approximately 1μm in size,. Fig. 2 show some results about the test aerosol produced.

In Fig. 2, it can be observed that a higher concentration could be obtained (> 100 particles/cm3) with this generation method. Most of the particles in the wind tunnel are generated by the smoke machine, and the influence of the other particles due to dust and pollution of the environment is low. Furthermore, the dispersion of the particles within the working section of the wind tunnel is another advantage of this generation method, because it makes the different measurements more repeatable.

From the evaluation of the two aerosol generation methods it has been seen that the second method, based on the dissolved sugar and the smoke generator, is more suitable for this research.

3.3 Wind Tunnel Test

Sugar particles (dissolved in distilled water and red food colouring) were dispersed, using the smoke machine, in front of the wind tunnel input duct.

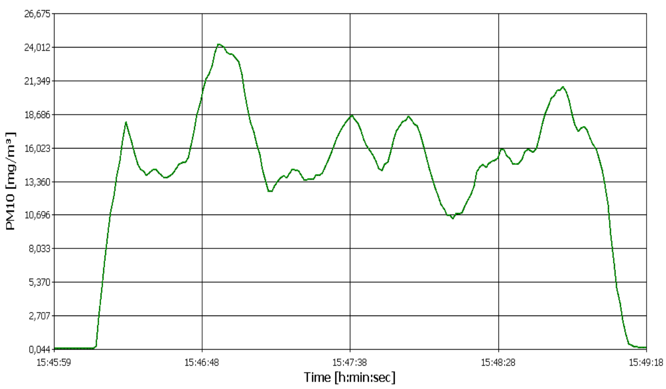


Fig. 3. PM10 Particle concentration level.

The wind tunnel has a velocity range of 3-50 m/s, a test cross sectional area of 300 by 300, a 1100 mm in length, a downstream contraction of 2300 mm, and a working section of 1200 mm. The EVM-7 was tested at three different velocities (20, 25 and 28 m/s), and for each velocity four 3-minute tests were conducted for the different impactors. Figure 3 shows the particle concentration measured with a PM10 impactor in an airstream of 28 m/s.

The notation PM10 is used to refer the cut size of the inlet and the impactor. With a PM10, only particles up to 10 µm can reach the sensing zone. Wind tunnel tests show that the air sampling device is capable to work at speeds similar to those experienced by the UAS (20-30 m/s) and that the speed variations do not affect significantly the accuracy of the measurements.

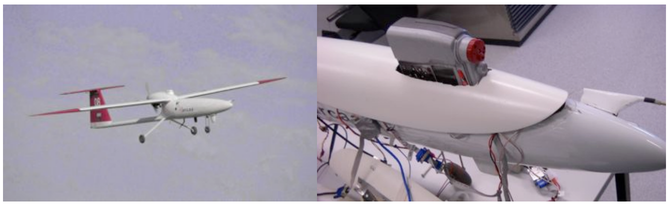
4 Installation and Integration process

An important step in the design of the air sampling system was the modification, installation and integration of the air sampling device with the Flamingo UAS platform.

4.1 Physical Installation

Before installing the air sampling unit on the UAS is essential to understand how the performance of the UAS would be affected. Considering the dimensions of the air sampling device (19x19x7 cm) and its weight (1.3 Kg) and the dimensions of the nose cone of the Flamingo UAS (95x24x17) as well as its payload capabilities (2Kg) , it was possible to adapt the instrument in the nose. This installation did not compromise the performance of the UAS since the weight of the air sampling device was within the payload capabilities of the UAS.

The payload bay, in the nose cone of the Flamingo, is divided in two compartments. For the air sampling instrument, we chose the front compartment, in order to leave the other one free for the MicroPilot, a small onboard computer and the batteries for the power supply of the servos. There were no problems related to power supply since the air sampling instrument works with an internal battery. As a requirement of the air sampling device it was necessary that the device pointed in the same direction of the flight. Since the standard cover of the upper nose of the flamingo was closed by a cover, it was necessary to make some modifications in order to fit it to the UAV. Part of the edges of the cover were removed in order to have room to install four metal plates, that allowed the air sampling sensor to be easily removed and attached the air sampling device before and after the air sampling mission.
The air sampling device was installed with the inlet parallel to the airstream and the nose cone cover of the UAS was modified in order to allow the inlet of the device to be exposed to the airstream.



a) b)

Fig. 4 a) System Architecture. Flamingo 'Carla' UAS in a flying mission. b) The air sampling device was installed with the inlet parallel to the airstream and the nose cone cover of the Flamingo was modified in order to allow the inlet of the device to be exposed to the airstream.

4.2 Integration

Two solutions for the integration of the device onboard the UAS were explored. The first was related to perform a datalog remote index-linked aerosol sampling, whilst the second involved obtaining and relaying data to the ground station in real time during the mission.

4.2.1 Data log-Index-linked sampling

In this first solution, the data would be captured by the air sampling and post processed after the flight. Here the air sampling device was not connected to the autopilot or to the radio modem onboard. Therefore, all the data collected during the air sampling mission was recorded and stored in the internal memory of the instrument. Time synchronization between the micropilot clock and the air sampling internal clock was performed before the flight. This adjustment was conducted in order to relate the time when the data was captured with its corresponding GPS location. As a result, it was possible to know where and when each particle or gas concentration level were detected by downloading the data from the instrument after the flight and comparing them with the GPS positions of the UAS obtained from the data log.

4.2.2 Real-time data monitoring

This solution is more complex, but allows monitoring of particle/gas concentration levels in real time. The air sampling has an analog output, which produces a signal (in voltage) continuously. The signal is proportional to the particle concentration level detected. The analog channel was configured to track settings on the sensor, according to the specific application. In order to send in real time to the ground station the concentration values measured, a STK-500 development system with an ATMega16 microcontroller was used. By means of the software AVRstudio, the microcontrollers were programmed to perform the conversion from analog to digital. The ADC and microcontroller sampling rate was set at 1 value per second first. However, if a specific application requires a more accurate sampling the AVRstudio code can be modified in order to obtain a higher sampling frequency of the analog signal. Fig. 5a and Fig. 5b shows the system architecture, which provides real time data monitoring.

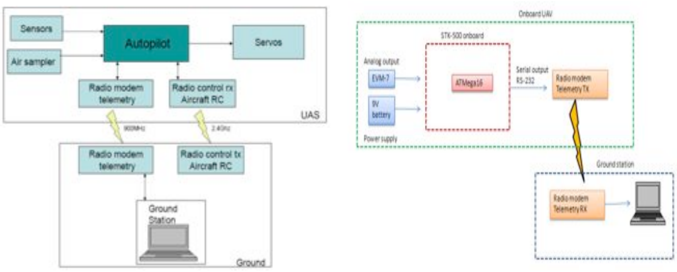


Fig. 5. a) Whole System architecture. b) System Architecture for real time monitoring of spores.

5 Mission and Design Simulation

Mission simulation is necessary to reduce flight testing time. Depending on the specific application of the air sampling system, different missions can be designed and simulated. Following a general approach to the mission design, we can define an air sampling zone to be kept under surveillance. The area of this zone can be different, depending on the application. Once the system architecture of our sampling system is established, different missions according to the dimensions of the area to be sampled can be planned. In fact, the limitations of the UAS platform (especially in terms of minimum turn radius) affect the optimal flight plan and the waypoint positions. The best position of the waypoints for a certain zone to sample depends primarily on the dimensions of the zone and secondarily on the weather conditions. If the area to be monitored is large or medium (400m x 700m), in relationship to the features of the UAS platform in terms of minimum turn radius, then a good structure for the waypoint position can be as reported in figure 6. Since the minimum turn radius for the Flamingo UAS is approximately 150 m in no wind conditions, the flight plan needs to be modified according to the wind direction.

The location of the map used for the simulation is at Burrandowan, QLD, ARCAA’s flight testing facility (8km2) where the flight tests of the UAS were performed. The dimensions of the simulated area to monitor are 400 x 700 m (Fig. 6a). A field of 400 x 700 meters can be considered large for the Flamingo UAS, because it can turn and remain inside the defined area.

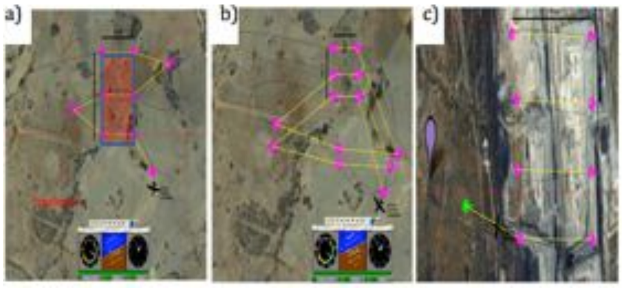


Fig. 6. a) Red box (400 x 700 meters) highlighted the field were the testing was performed at Burrandowan. b) Field 220 x 300 meters Burrandowan. c) Goonyella Riverside, QLD, Australia simulated mission.

Hence, six active waypoints have been positioned near the border of the field, and three navigational waypoints were positioned outside. Active waypoints are those inside the area to be monitored and navigational waypoints are those outside, which are useful only to perform the mission. In this manner, the area can be monitored with three paths, each separated from the other by a turn. The simulation was performed at a fixed target altitude. An example of this application is a sugar plantation, in which the presence of pollen and spores at a certain altitude has to be detected.

If the area to be monitored is relative small compared to the turn radius of the UAS, another flight plan has to be developed. The position of the waypoint is reported in figure 6. In this case, the dimensions of the simulated field are approximately 220 x 300 meters. If we want to perform an accurate sampling of the area, with six active waypoints and three different paths over the area, it is necessary to use more navigational waypoints. In this manner, the Flamingo UAS can fly out of the field and cross it always in the same direction (for example from west to east). The problem of this waypoint structure is that the UAS spend a lot of time flying out of the field, overflying areas, which are of no interest.

Two practical applications have been explored in simulation: an open mine monitoring and a volcano monitoring. In the first application, we are interested in detecting particles of different sizes and evaluating the concentration level. In the second application, the aim is to monitor the gas concentration level over an active volcano.

5.1 Sampling at low level altitude: Goonyella Riverside coal mine (Australia)

Located at about 30 km north of Moranbah, in central Queensland, Goonyella Riverside open cut coal mine produces high quality coking coal for costumers in Asia, Europe, Middle East and India. The dimensions of the operational area of the mine are about 22 km long and 10 km wide. In an open mine, depending on the weather conditions, the level of dust and particle concentration (of different sizes) in the air can reach values that are dangerous for the health of the workers. It is important to monitor the air over the mine in order to keep the quality of the air for the workers and population in nearby towns under control.
To monitor an area of these dimensions, a single air sampling mission is not enough. This is due to the limitations of the UAS platform in terms of range; in fact the Flamingo can cover safely an area of about 6 km by 6 km from the ground station. Moving the ground control station after each mission and finding a different runway every time is logistically very complicated. Therefore, the solution of this problem is to have different platforms, each monitoring different and most critical regions of the mine. As designed the air sampling system can be installed on a larger UAS with similar avionics (communication protocols, autopilot) as those on the Flamingo UAS. The simulation is conducted in the south part of the mine in an area of about 1.6 km by 2 km. Fig. 6 shows the simulated flight of the Flamingo over the mine. The violet marker shows the location of the ground station, near the runway. The main data for the simulation is reported in Table 1.

TABLE I
SIMULATION DATA

Parameter	Goonyella Riverside	Isola di Volcano
Sampling altitude (m)	110	260
Target speed (Km/h)	94	94
Active waypoints	8	8
Nav. waypoints	1	1

5.2 Isola di Vulcano (Italy)

Isola di Vulcano is an island of about 21 square km, belonging to the archipelago of Eolie, Italy. This active volcano is located in the north-west part of the island; its eruptions are frequent and usually explosive. The products generated by volcanic activity can be very different: from solid materials, such as volcanic rocks, ashes and pyroclasts, to gases. The main gas produced is water vapour, with a concentration varying from 50% to 98%. However, also CO, CO2, H2 and compounds of sulphur, nitrogen, chlorine and fluorine are usually produced by the volcanic activity. Monitoring the air over an active crater is very important, as the cloud of gases and dusts produced even during a small eruption can be very toxic and dangerous. The area to be monitored in this application can be framed in a rectangle of about 1.2 km by 1 km. These dimensions allow a single mission to sample all the area. The main data for the simulation is reported in table 1.The main issue of an air sampling mission simulation over a volcano is the altitude. In this case the simulated ground station is at 220 m above sea level, and the highest point of the area is at about 370 m above sea level.

For this reason, setting the sampling target altitude at 110 m (as done in the previous case) would cause a probable crash. Therefore, the sampling altitude was set at 260 m (150 m of distance between the ground station and the highest point of the crater, plus 110 m of safe altitude). Results of the simulation are reported in Fig. 7.

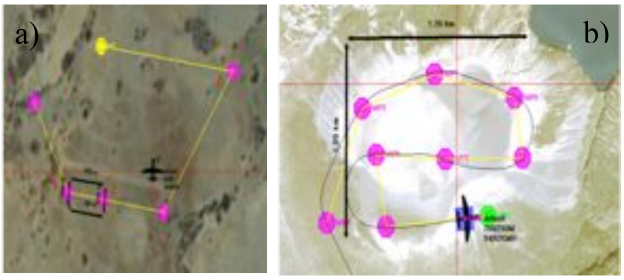


Fig. 7. a) Path following flight plan. b) Isola di volcano, Eolie, Italy, simulated mission.

6 Flight Testing

The first step in order to perform the flight tests of the air sampling system, is generating a flight test plan. It is necessary to choose the location and clarify the purpose of the tests. It is also important to detail the test methodology, with an estimate of the time required to perform each test, and the risk analysis and mitigation.

6.1 Flight test and Location

The tests were conducted during February 2010. The location chosen was a farm at Burrandowan (approximately 80*km* from Kingaroy, Queensland, Australia). This location was chosen as ARCAA has operational experience conducting flight tests in the region for three years. The complexity of flight test was reduced since the surface of the area is nearly flat.

6.2 Purpose

The purpose of the flight tests is to prove the logging capabilities of the air sampling system and the ability of the UAS to perform a stable and safe flight with the air sampling device in the payload bay. In addition, we wanted to prove the capability of the air sampling device to monitor particle flying on an UAS and the capability of the air sampling system to perform a safe autonomous mission in a real environment.

6.3 Methodology

6.3.1 Environmental Test

The aim of this test was to record data about the environmental levels of particle concentration at the flight test location, in order to know the levels of dusts in the area, which could affect the measurements, and have reference values for the following tests. Fig. 8a shows the particle concentration levels measured by the device in the in the flight test area.

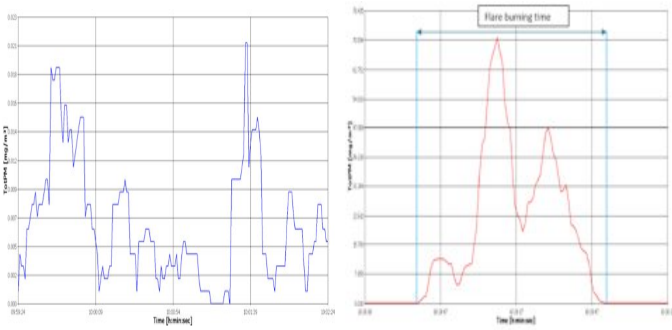


Fig. 8. a) Tot PM particle concentration level vs time (0 m/sec, 3 min sampling time, no smoke) b) Tot PM Particle concentration level vs. time (wind speed 5 m/sec, total sampling time 3 min, red flare).

It is possible to observe that the maximum concentration level recorded with the TotPM impactor is 0.021 mg/m3. These concentration values are very low, also compared to the values recorded during the wind tunnel tests. This was helpful for the following tests, because the releases gases could not be confused with factors due to the external environment.

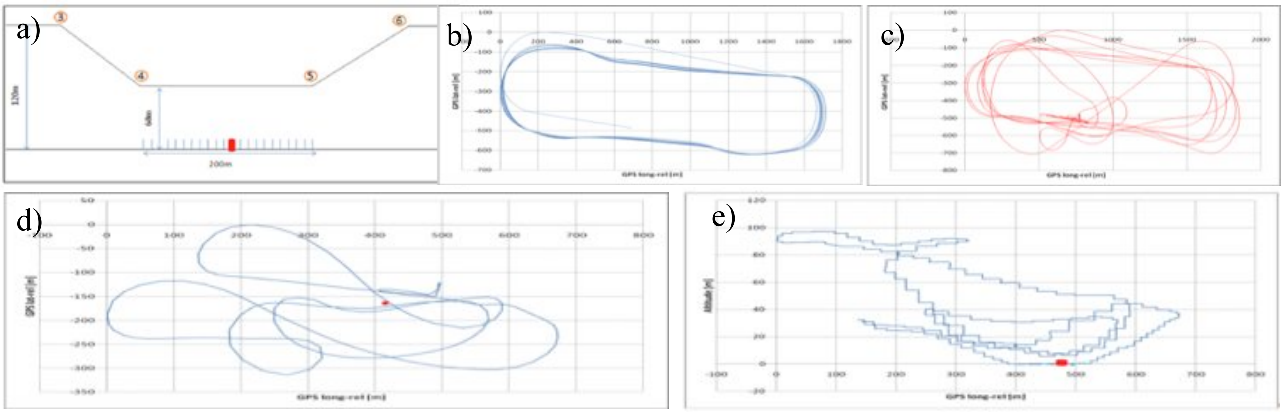


Fig. 9. a) Schematic of the flight path. b) GPS (x,y) coordinates, simulation. c) GPS (x,y) coordinates flight test. d) GPS (x,y), air sampling simulation. e) GPS speed vs time, flight testing.

6.3.2 Ground Test

The aim of this test was to verify the capabilities of the system to detect particles or gases generated by a smoke flare at a close range distance. Additionally another goal was to obtain the necessary reference values at a close range distance. The device was set on a table and a red hand flare was lighted up at 3 meters from the air sampling device. The burning time of the red flare was 60*s*. Fig. 8b shows the particle concentration levels measured by the device. The particle concentration values recorded with the TotPM impactor are the highest ever recorded in this research (maximum concentration of 71.3 *mg/m3*). This validates the red flare as a good test aerosol generation method for the flight testing of the air sampling system. The presence of peaks of concentration during the flare burning time is observed and is due to variable wind condition.

6.2.3 Path Following

A simple path following was performed using the waypoint structure reported in Fig. 7 a. The monitored area is a small field of about 200*m* by 100*m*. This simulates an agricultural application, in which a sugar cane field has to be monitored in order to check fungal spores concentration, or monitor a gas concentration near a volcano. The UAS has to fly at two different altitudes: a safe altitude of 400 *ft* (about 120*m*) outside the simulated sugar cane field or further to the volcano and a sampling altitude of 200 *ft* (about 60*m*) inside the simulated sugar cane field or closer to the volcano. Once it reaches waypoint 5, the UAS climb again at the safe altitude. Fig. 8a shows a schematic of the flight over the field area.

The red marker indicates the location of the flare that will be lighted up during the tests to simulate a high spore concentration. A simulation of the flight plan was performed initially, in order to obtain a simulated telemetry and to compare it with the telemetry of the flight test. From the analysis of the standard telemetry, four plots of the path followed by the UAS were obtained. Fig. 9b and Fig. 9c show a comparison of a plot of the path followed by the UAS during flight test with the telemetry results from the simulation. Even though the weight of the air sampling device is not considered in the simulation, it can be observed that there is a good correlation between the simulation and the actual flight test. The variations of the boundary conditions (such as wind speed and direction) during the actual flight test also cause the difference between the results. Considering the GPS speed (Fig. 9a and 9b), we can observe that there are large fluctuations of the speed near the value of the target speed for the actual flight test. The altitude changes (from a safe altitude to sampling altitude) amplify the speed fluctuations. However, these fluctuations are not a real problem for the air sampling mission, because the air sampling system is able to adjust the internal flow rate according to the pressure drop measured. Therefore, the air sampling system proved to be able to fly autonomous while following a flight path at a safe altitude.

6.2.4 Air Sampling Mission

Air sampling at low altitudes may present several safety issues for the UAS. In this experiment, this risk was present since the smoke generated by the flare was dispersed by the wind only few meters above the field (not more than 20). For this reason, it was necessary to fly at lower altitudes than the previous sampling altitude of 200*ft* in order to capture the particles generated by flare. Autonomous flight at the target altitude of 20*m* (near the red flare) was not safe, due to the limitation on altitude and GPS accuracy, therefore that section of the air sampling mission was performed in RC mode. After the take off of the air sampling system, the red flare was lighted up at the border of the runway(Fig. 9). During the burning time of the flare, the air sampling system had time to perform three low altitude passes. One of these is shown in Fig. 11 a.

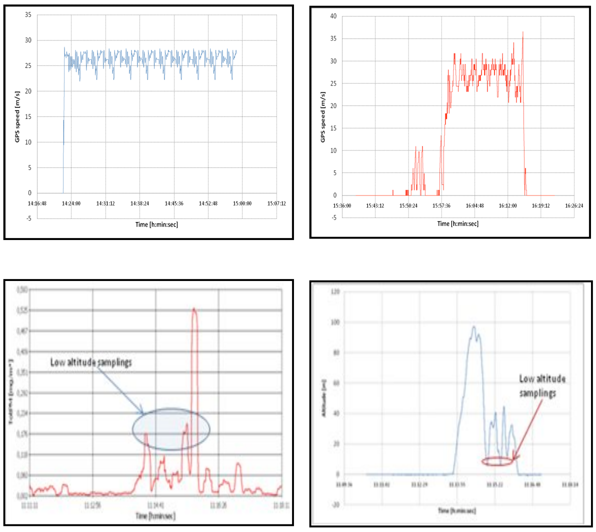


Fig. 10 a) GPS speed vs Time simulation. b) GPS speed vs Time flight test. c) GPS (x,y) coordinates, air sampling mission. d) Altitude vs time, air sampling mission.

Fig. 10 show the results obtained from the analysis of the telemetry. Fig. 10c is the top view of the UAS's trajectories during the tests, Fig. 10d shows the trend of the altitude versus time. After the take-off and the climb, it is possible to observe three passes at low altitude performed by the UAS. The particle concentration values measured during the mission were transmitted to the ground station in real time, at the same logging rate of the air sampling device (one data per second), and appeared as voltage through the ground station HyperTerminal. All the values were also recorded within the internal memory of the instrument, to be downloaded after the mission. The plot with the concentration values recorded during the mission is presented in Fig. 10a. From the comparison of this plot with the plots obtained from the telemetry, it possible to observe that the peak of particle concentration was recorded in correspondence of a pass of the air sampling system at low altitude over the burning red flare. Fig. 11b shows particle concentration data recorded and the flight log GPS telemetry data. As expected, the Fig. shows higher particle concentration near the flare and downwind.

7 Conclusions

In this research an airborne air sampling system for Unmanned Aerial Systems (UAS) platforms that could provide capabilities for detection of particle and gas concentrations in real time over remote or dangerous locations was developed. A system architecture, which is based on the integration of a multifunctional air sampling instrument, with capability for simultaneous measurement of particle and gas concentrations, with the QUT/ARCAA UAS platform communications protocols, was chosen and developed. Result of the integration process shows a system that is capable of both real time monitoring and indexed-link sampling.
Wind tunnel tests were conducted and experimental data was used to evaluate the performance of the air-sampling instrument in controlled non-stationary conditions, at the typical operational velocities of the UAS platform. The main result of these tests is that the airspeed (up to 30 m/s) does not affect the performance of the system in detecting particles and gases. An internal pump (based on a sensor that measures the pressure drop across the inlet orifice) provides a constant flow rate. Once a remote fully operative air sampling system, with the ability of geo-locate and spatially monitor gas and particle concentrations, was developed, the problem of mission design was analyzed through simulation and flight testing of different

scenarios. As result of this study, it was found that the target sampling altitude is the main issue in an air sampling mission.

a)
b)

Fig. 11. a) UAS path on the map and particle concentration (mg/m3). b) Low altitude pass over the red flare.

Flight tests of the complete air sampling system were conducted to prove its capability performing air sampling mission following a specific flight path. The system demonstrated to be able to operate in a real environment detecting particle and gas concentration levels. Future work will focus on adding a more accurate altitude sensor for low altitude and performing the mission over a region of interest and determining the influence of dusts or ashes on the telemetry data and transmission.

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